STAR Physics Program

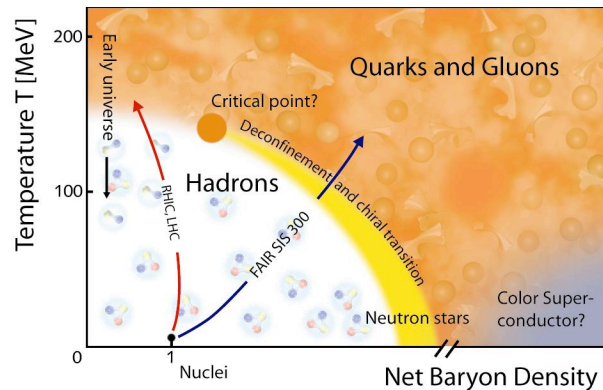**Nu Xu**

Nuclear Science Division
Lawrence Berkeley National Laboratory

STAR Detectors: *Full 2π particle identification!*

TPC

TOF

EMC+EEMC+FMS
($-1 \leq \eta \leq 4$)

DAQ1000

HLT

HFT
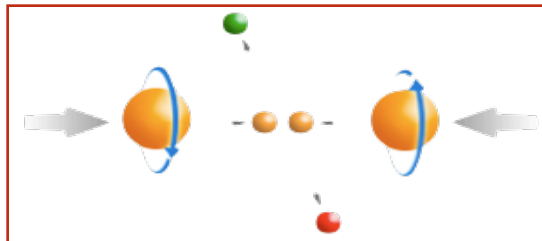
FGT
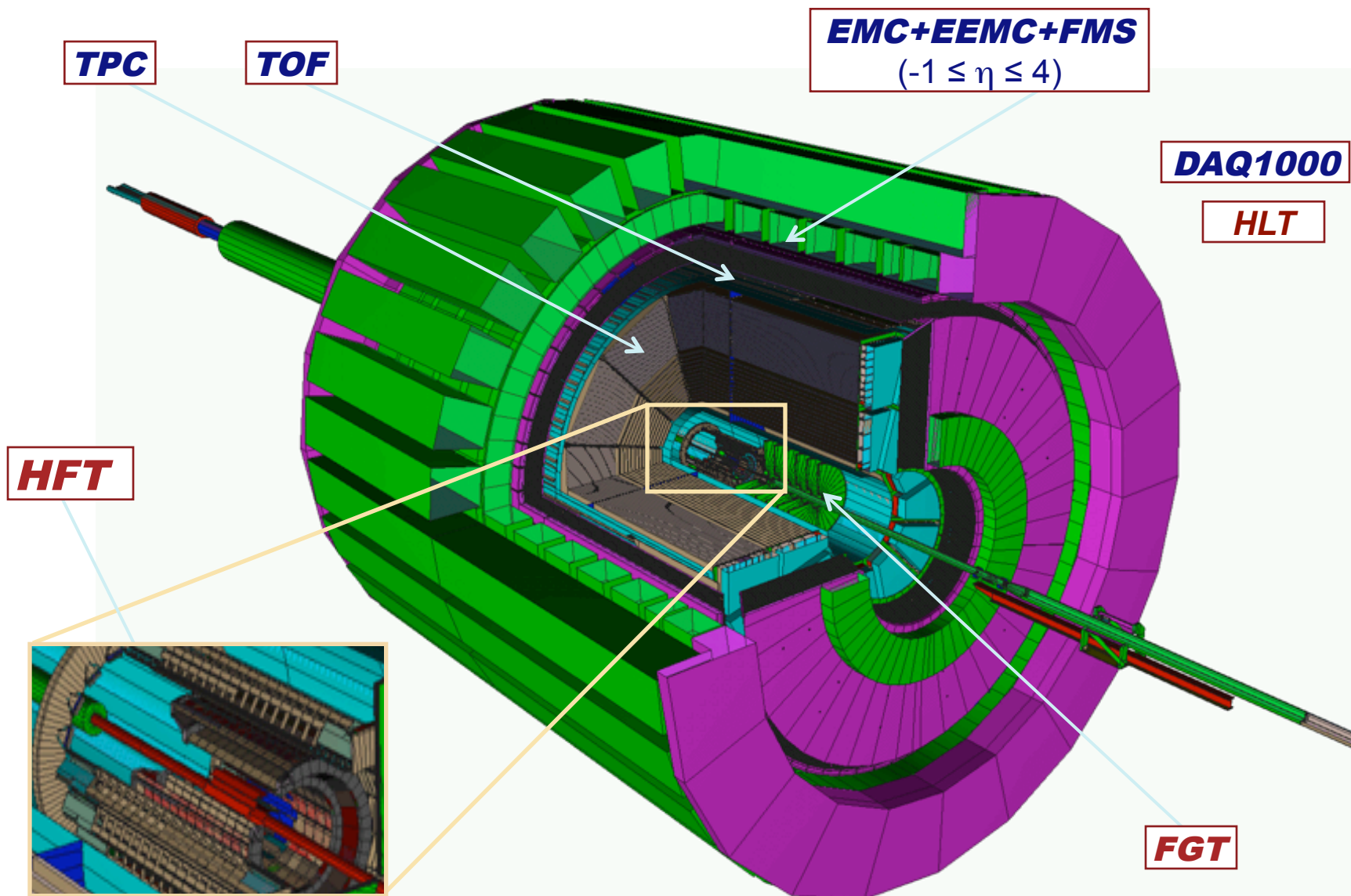
STAR Physics Focus

1) At 200 GeV top energy
- Study *medium properties, EoS*
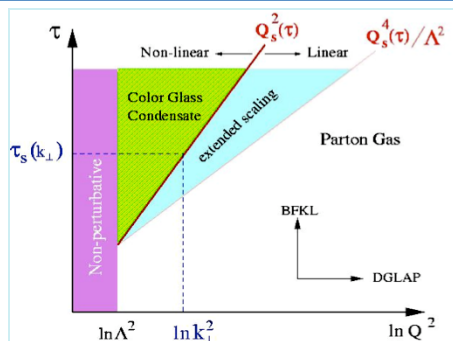- pQCD in hot and dense medium

2) RHIC beam energy scan
- Search for the *QCD critical point*
- Chiral symmetry restoration
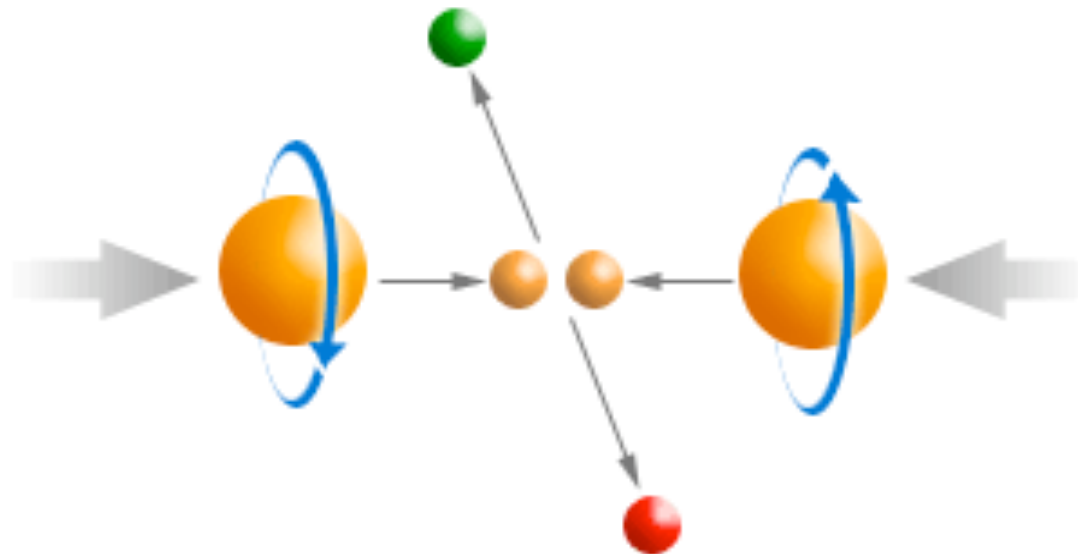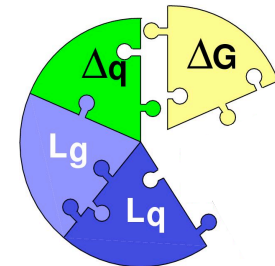
Polarized spin program
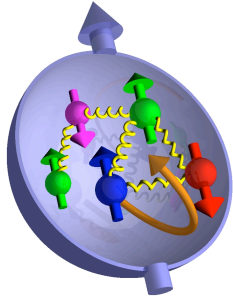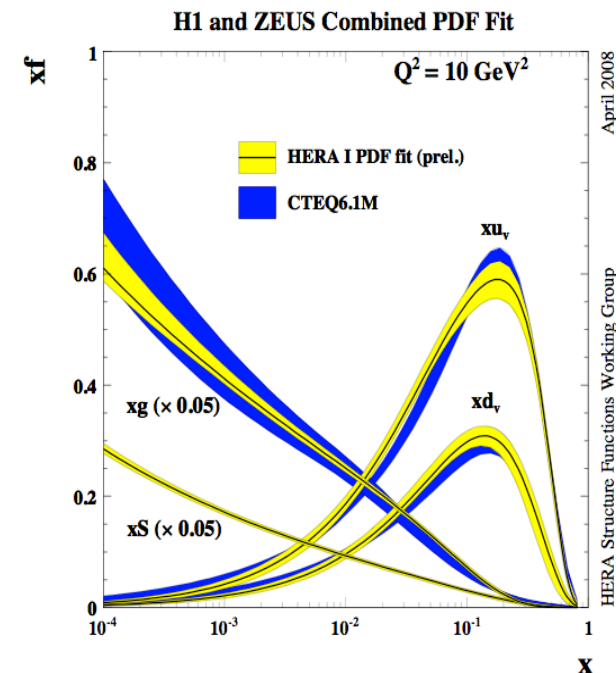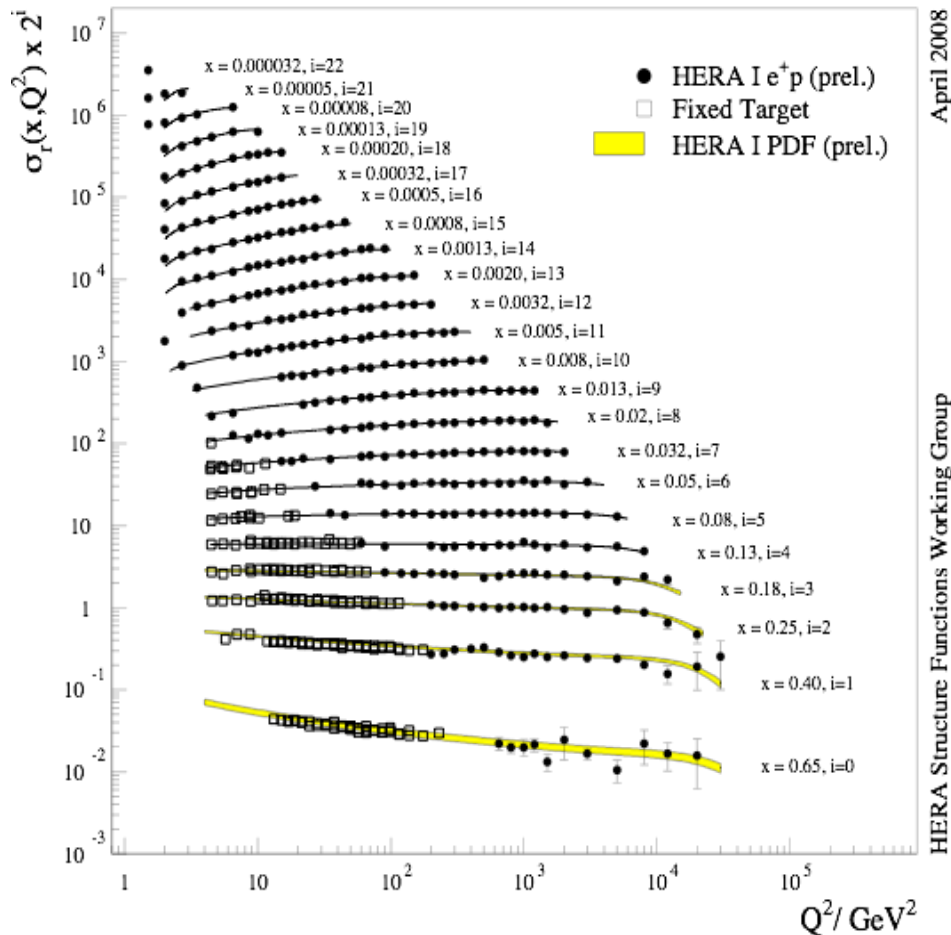- Study *proton intrinsic properties*

Forward program
- Study low-x properties, search for *CGC*
- Study elastic (inelastic) processes (pp2pp)
- Investigate *gluonic exchanges*

Proton Spin Physics

Nucleon Structure Function

Precision measurements (e.g. F_2) $\Rightarrow$ ***Precision on q/g structures***

f(g) >> f(q) at small x!
Rich QCD phenomena.

Polarized *p*+*p* Program at RHIC
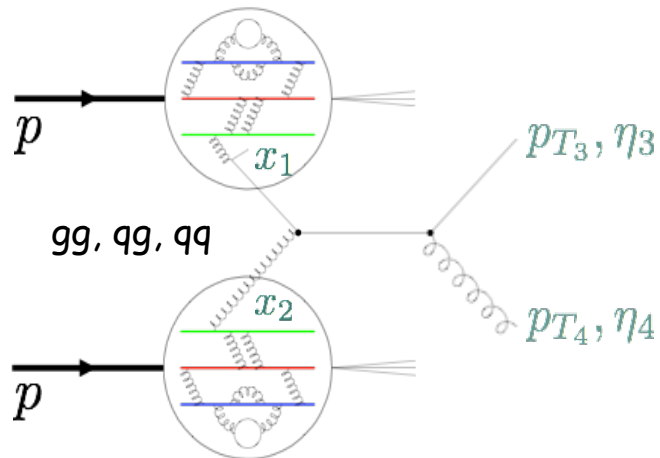
STAR: Large acceptance for correlation measurements

di-jets/hadron and γ-jet

$$x_{1(2)} = \frac{1}{\sqrt{s}}\left[p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)} \right]$$

$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln\frac{x_1}{x_2} \qquad \cos\theta^* = \tanh\left(\frac{\eta_3 - \eta_4}{2}\right)$$
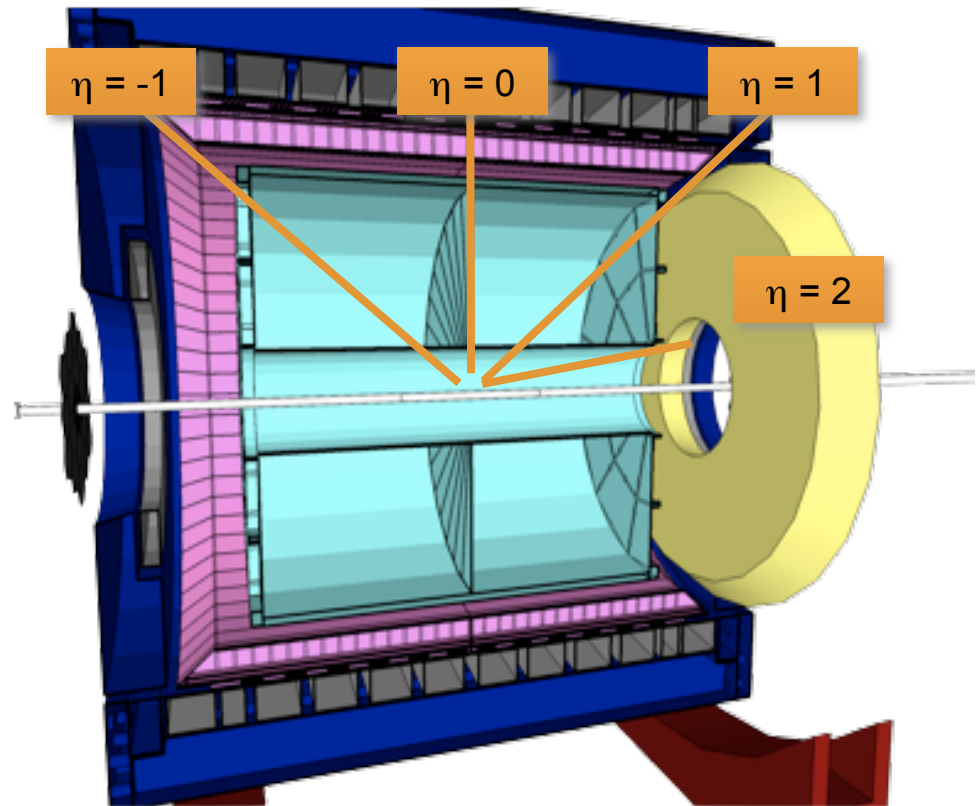
Δg Measurements at RHIC

Partonic Processes

Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)

$$x_T = 2p_T/\sqrt{s}$$
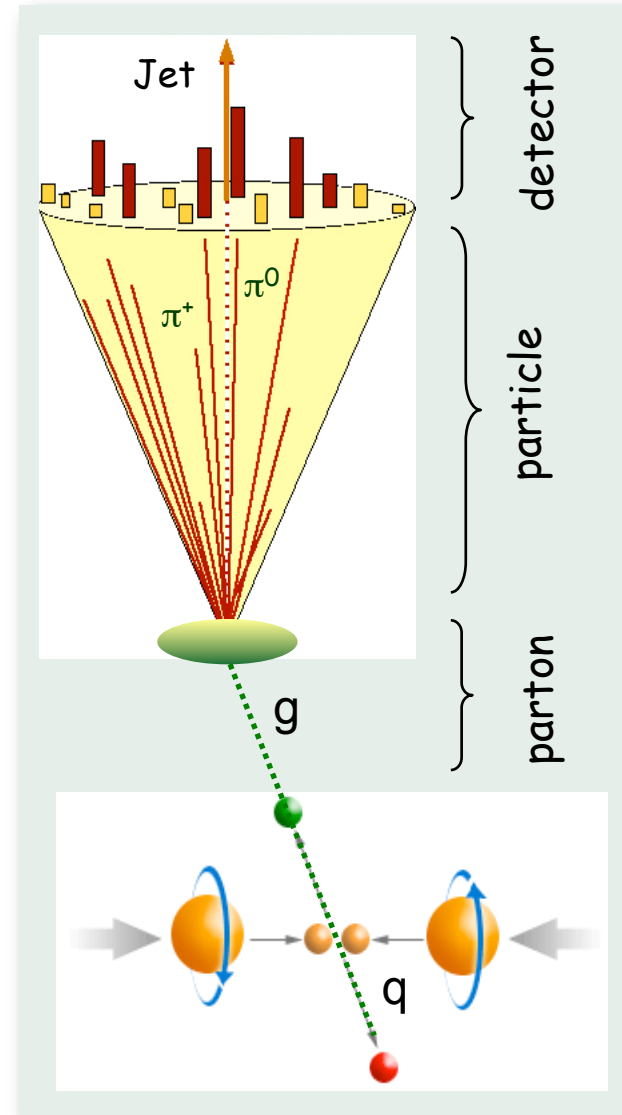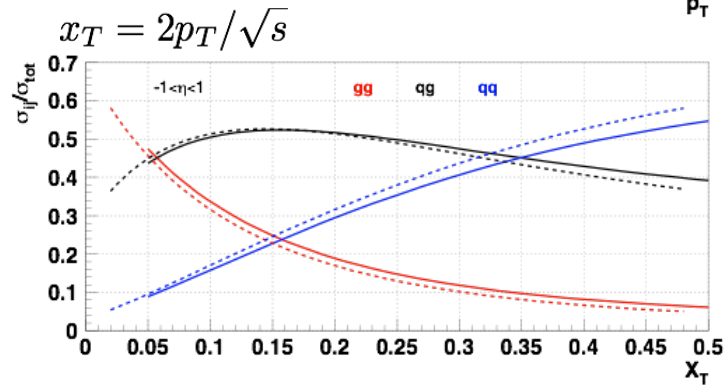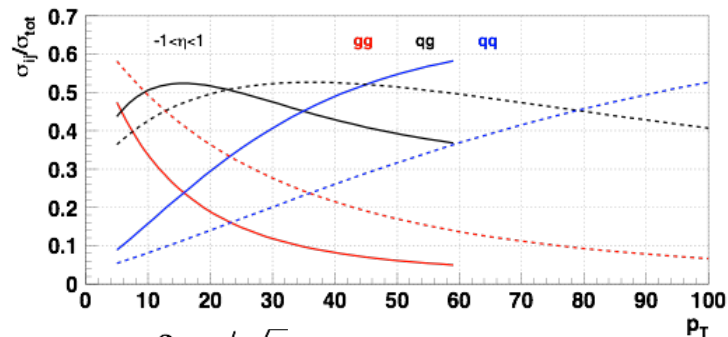
Status on *Δg* Measurements at RHIC

Run9 plan: STAR bottom line is to collect **FoM: 6.5 pb⁻¹** (Run9: 2.3 pb⁻¹)
inclusive jet, di-jets, γ-jet… analysis
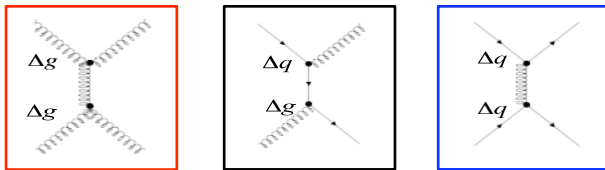
STAR: internal review of the *strategy* for spin physics in light of Run9 data. (Sichtermann, Sowinski, Surrow)

Run6
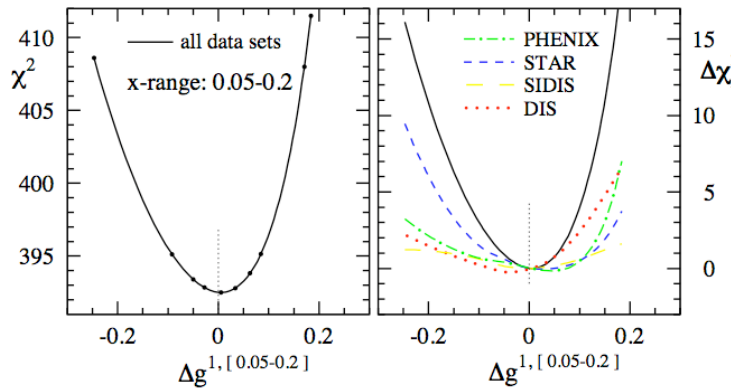
Run9 plan
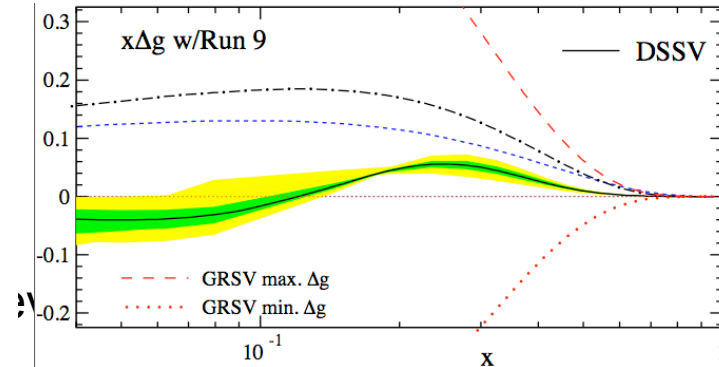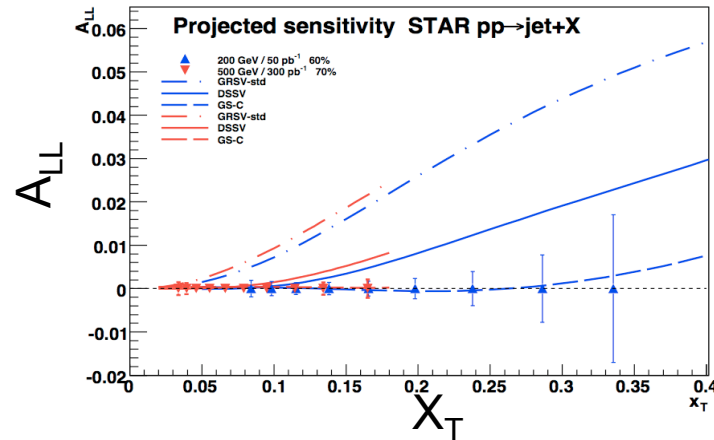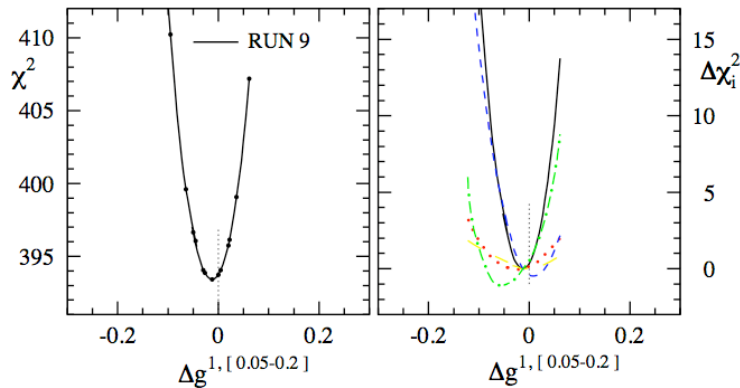
de Florian et al, arXiv: 0804.0422

STAR: 500GeV Low-x Program
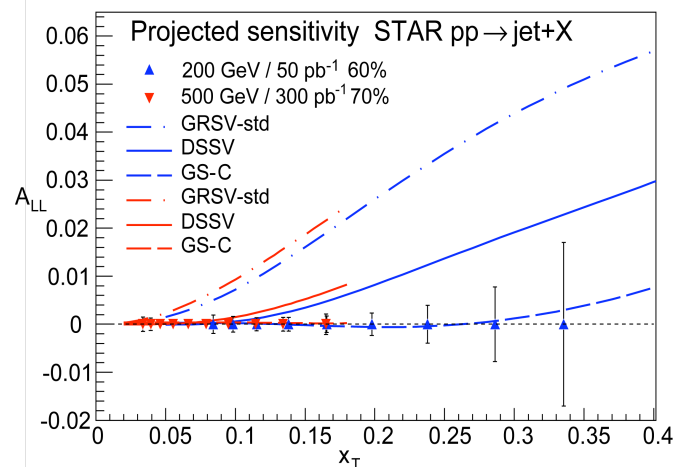
1) **High precision at √s = 500 GeV at small x, ~ 300pb⁻¹**

2) **Inclusive Jets**

3) **di-jet**
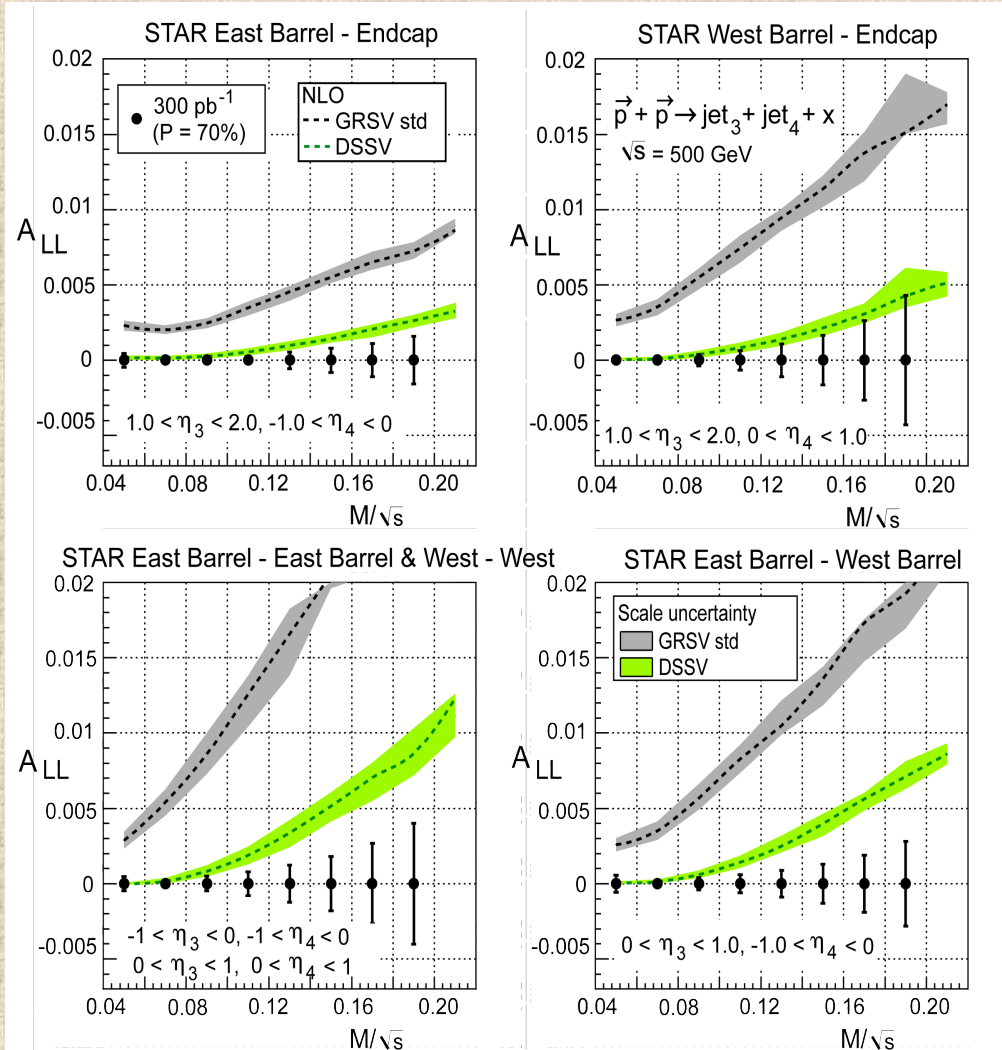
STAR: The *Sea-Quark* Program

500 GeV p+p collisions
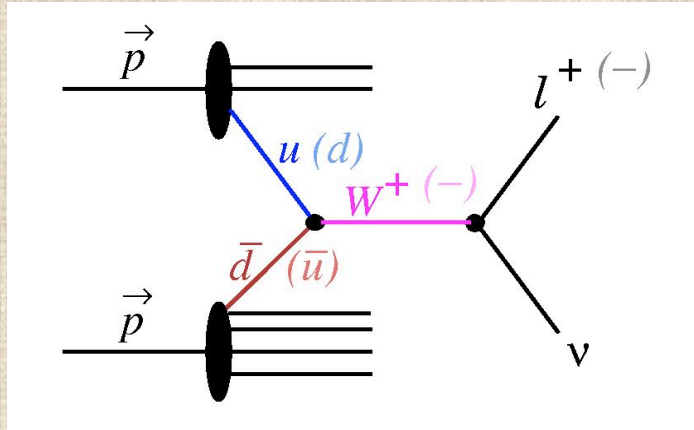
$$u + \overline{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

$$\overline{u} + d \rightarrow W^- \rightarrow e^- + \overline{\nu}$$

Forward GEM Tracker: FGT

1) Charge sign identification for high momentum electrons from $W^{\pm}$ decay (Energy determined with EEMC)

2) Triple-GEM technology, Summer 2011 for Run12
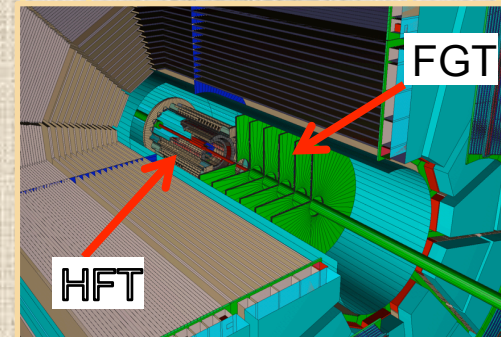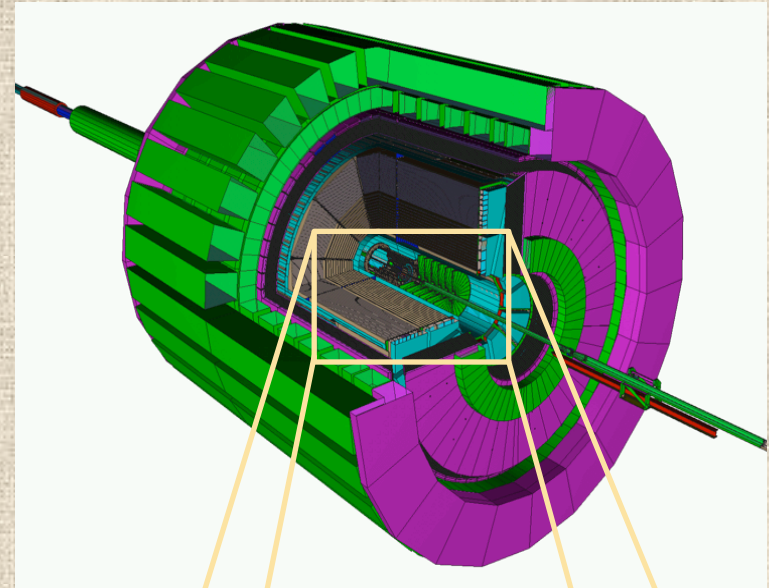
Forward Small-x QCD Physics

d + Au Collisions at RHIC

STAR Run−8 d+Au Configuration
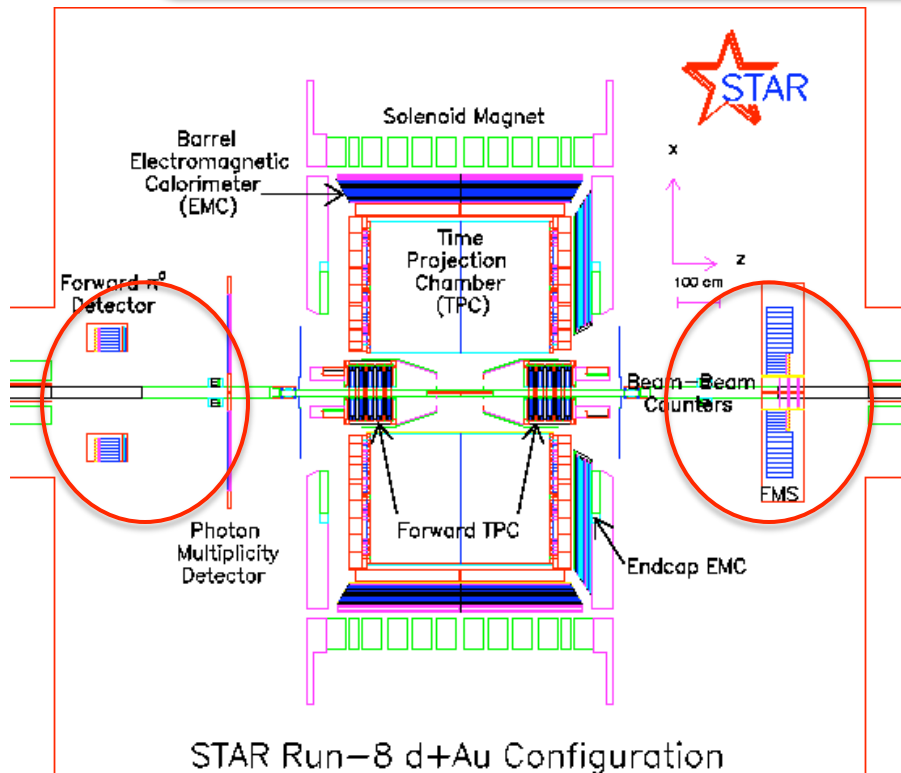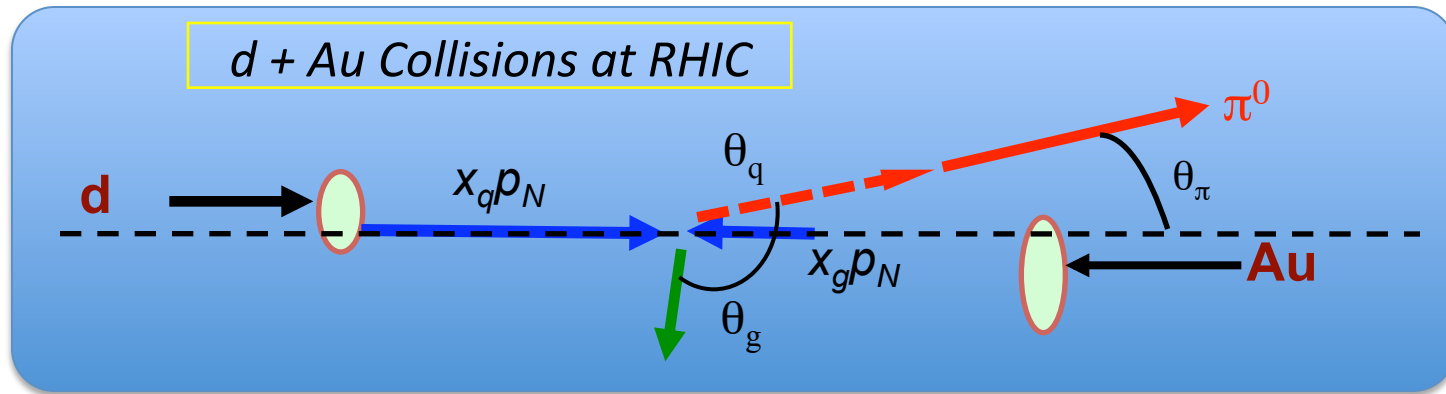
(1) <u>200 GeV *d+Au*</u>:

- forward small-x, scattering of asymmetric partonic collisions
- high-x valence q: $0.25 < x_q < 0.7$, large polarization
- low-x g: $0.001 < x_g < 0.1$

➔ Color Glass Condensate: parton structure function. Theory: $x_g \sim 10^{-4}$

(2) <u>200/500 GeV *p+p*</u>:

➔ Transverse spin phenomena: Siver or Collins effects

Fundamental QCD issues!

High-Energy Nuclear Collisions

sQGP and the QCD Phase Diagram

In 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- **Jet energy loss: R_{AA}**
- **Strong collectivity: v_0, v_1, v_2**
- **Hadronization via coalescence: n_q-scaling**

Questions:

Is thermalization reached at RHIC?
- **Systematic analysis with dN/dp_T and dv_2/dp_T results…**
- *Heavy quark and di-lepton measurements*

When (at which energy) does this transition happen?
What does the QCD phase diagram look like?
- *RHIC beam energy scan*

High-Energy Nuclear Collisions

1 Energy Frontier
T_C
LHC, RHIC

2 Density Frontier
T_E
RHIC, FAIR

3 Baryon Density
1st order p.b.
FAIR, NICA, CSR

Temperature

Early Universe

quark-gluon plasma

T_c

Critical Point?

hadron gas

nuclei

CSC

Baryon Chemical Potential
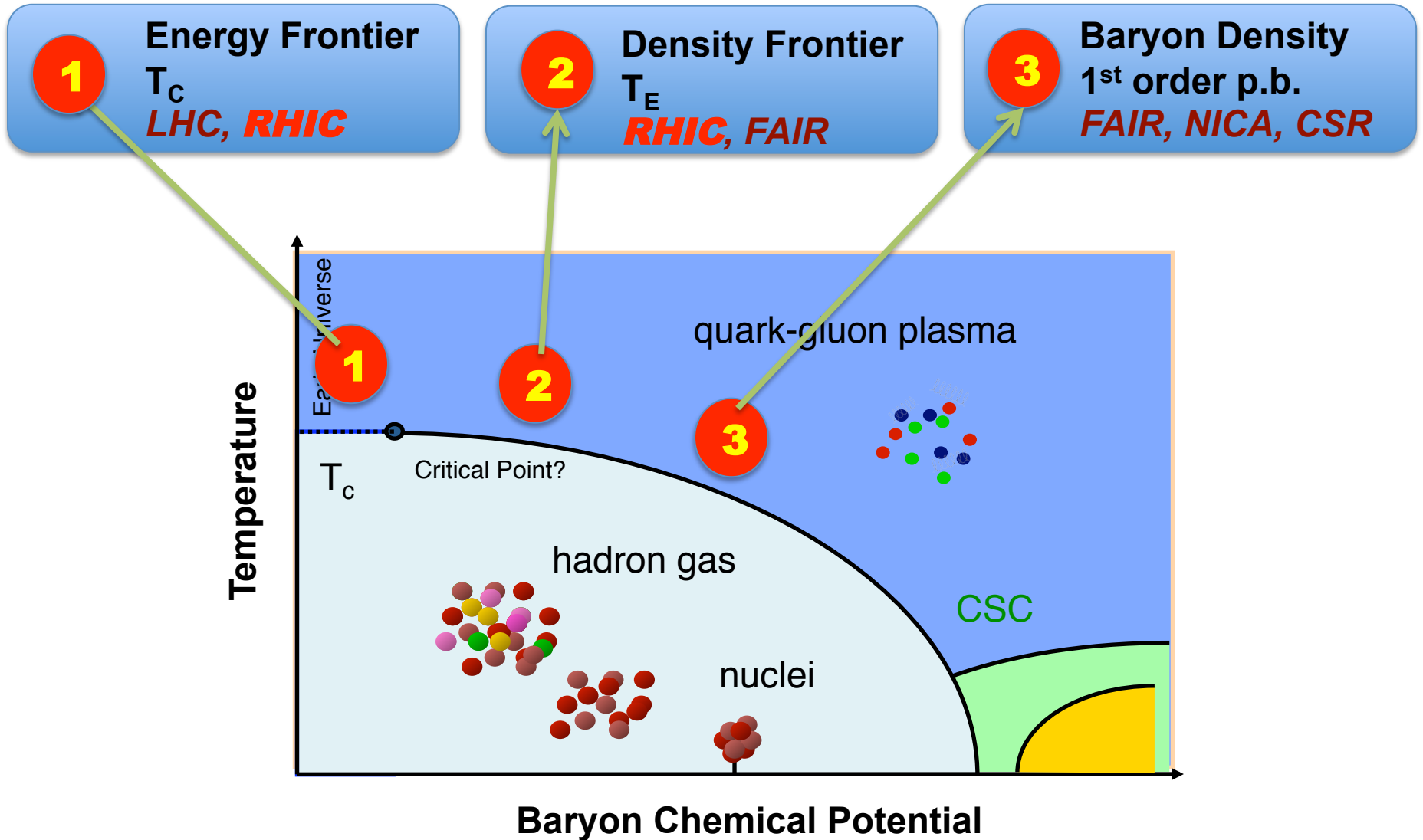
QCD Thermodynamics
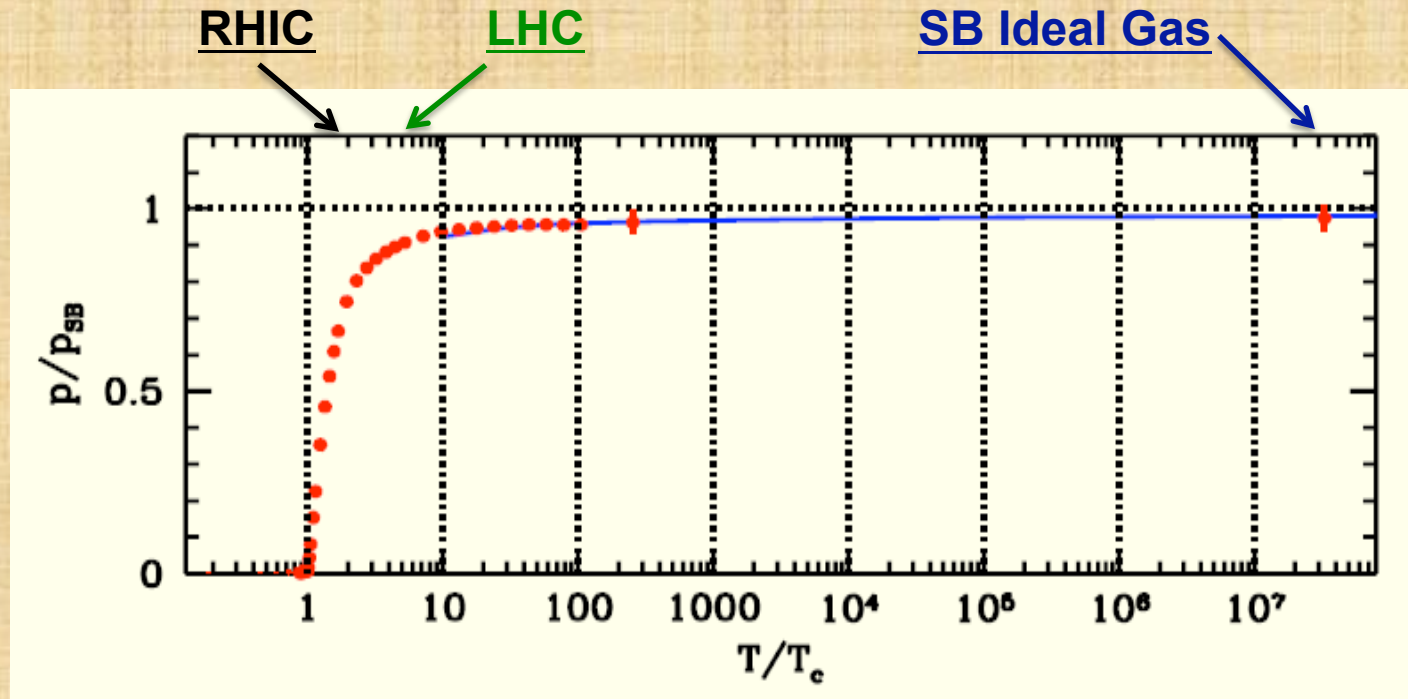
1) At $\mu_B = 0$: cross over transition, *150 < T_c < 200 MeV*

2) The SB ideal gas limit: $T/T_c \sim 10^7$

3) T_{ini} (LHC) ~ 2-3*T_{ini} (RHIC)

4) Thermodynamic evolutions are similar for RHIC and LHC

Zoltan Fodor, Lattice 2007

Search for Local Parity Violation ...

L or *B*
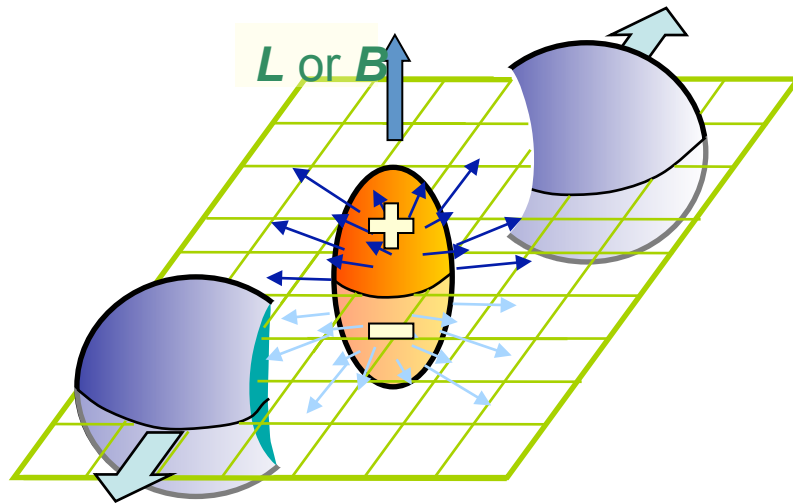
The separation between the same-charge and opposite-charge correlations.

- **Strong EM fields**
- **De-confinement and Chiral symmetry restoration**
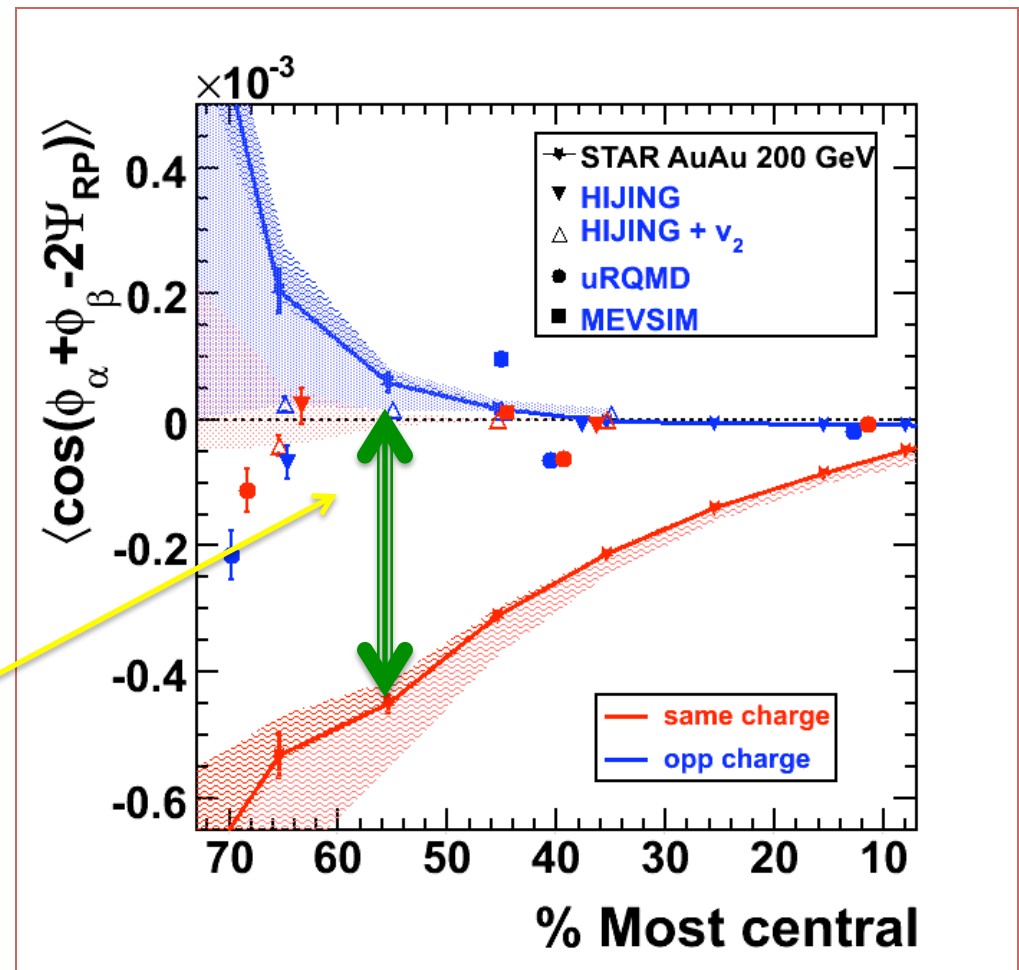
- PID LPV analysis with TOF
- RHIC BES: disappearance

$\times 10^{-3}$

$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$

- STAR AuAu 200 GeV
- ▼ HIJING
- △ HIJING + v_2
- ⬟ uRQMD
- ■ MEVSIM

same charge
opp charge

% Most central

Partonic Collectivity at RHIC

$\sqrt{s_{NN}}$ = 200 GeV ^{197}Au+^{197}Au Collisions at RHIC
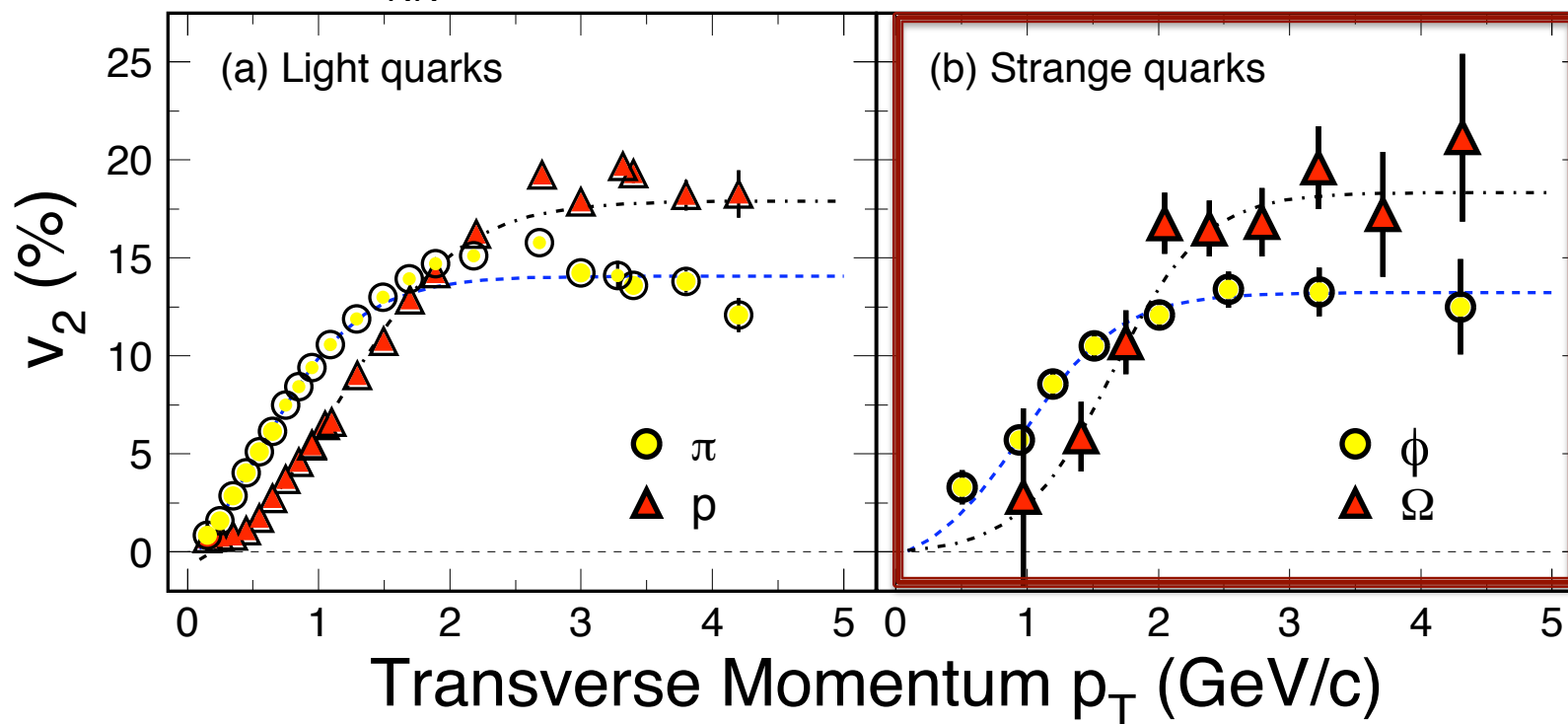
Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): number of quarks ordering
  s-quark hadron: smaller interaction strength in hadronic medium
  light- and s-quark hadrons: similar v_2 pattern

=> Collectivity developed at partonic stage!

Current Measurements with *J/Ψ*

Run10, √s_NN = 200 GeV Au+Au collisions:

1) Measure the v_2 of *J/Ψ*, with the help of HLT
2) Measure the R_{AA} of *J/Ψ* at high transverse momentum p_T > 5 GeV/c

Flavor Dependence in R_{AA} and pQCD
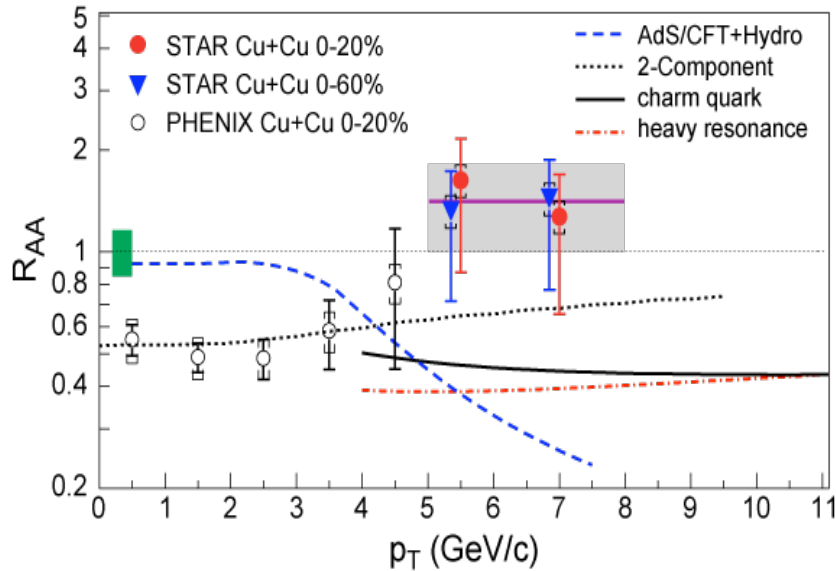
STAR submitted to PRL 0904.0439
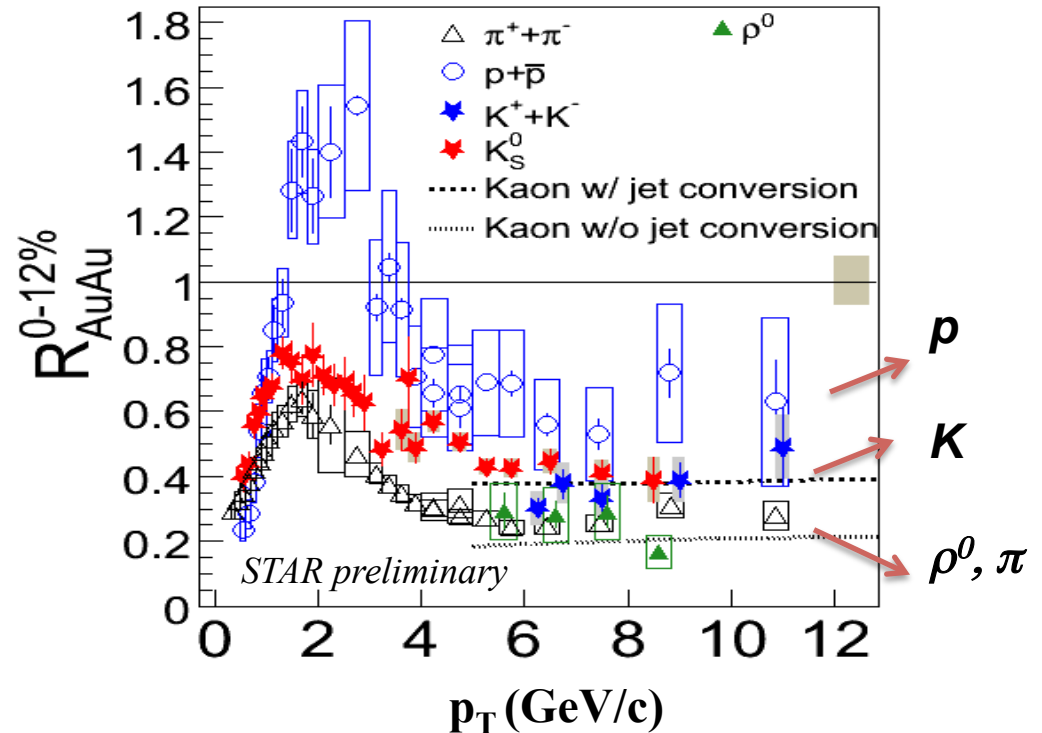
At $p_T \geq 5$ GeV/c: $R_{AA}(\pi) \sim R_{AA}(\rho^0) < R_{AA}(K) < R_{AA}(J/\psi)$

First Observation of $^3_{\bar{\Lambda}}\overline{H} \rightarrow {}^3\overline{He} + \pi^+$

AuAu200_Combined_Anti-$^3_{\bar{\Lambda}}$H_candidate

STAR Preliminary

• signal candidates

— rotated background

$^3\overline{He} + \pi^+$ InvMass
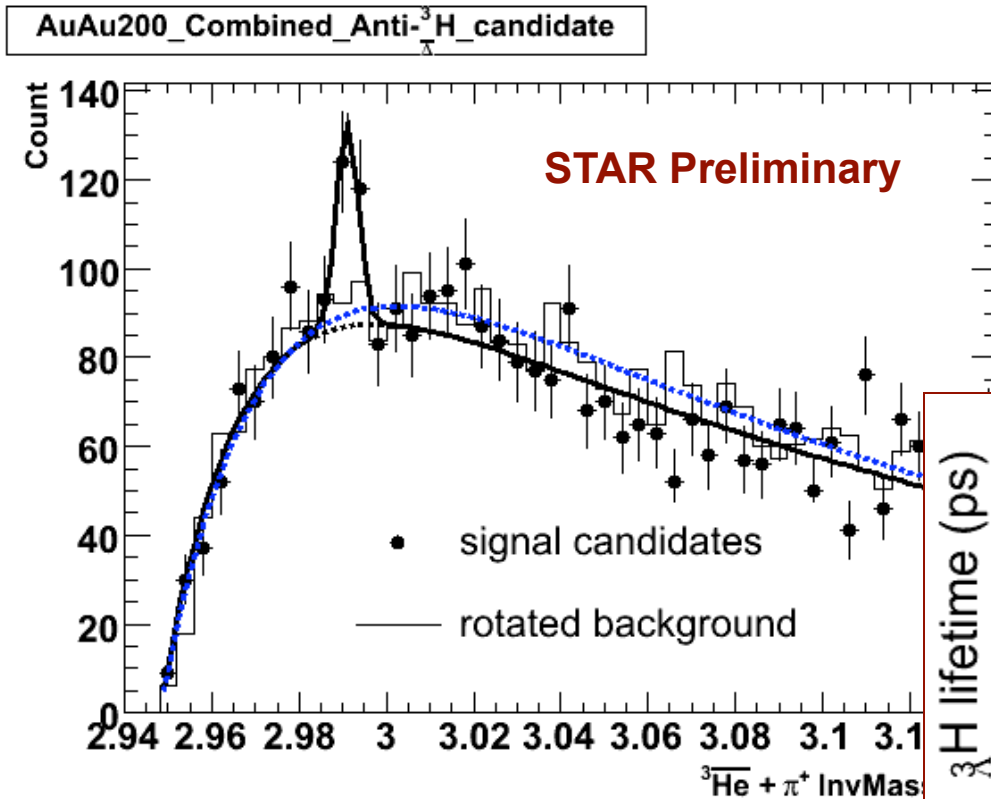
First observation of
an anti-hypernucleus

Paper draft in STAR review,
intended for the *Science*

200 GeV Au+Au collisions at RHIC

STAR Preliminary

PRD1, 66(1970)

PR180, 1307(1969)   NPB67, 269(1973)

PRL20, 819(1968)

STAR free Λ

STAR

NPB16, 46(1970)

PR136, 6B(1964)

- - - - free Λ
—— PL1, 58 (1962)
—— PRC57, 1595 (1998)

World data
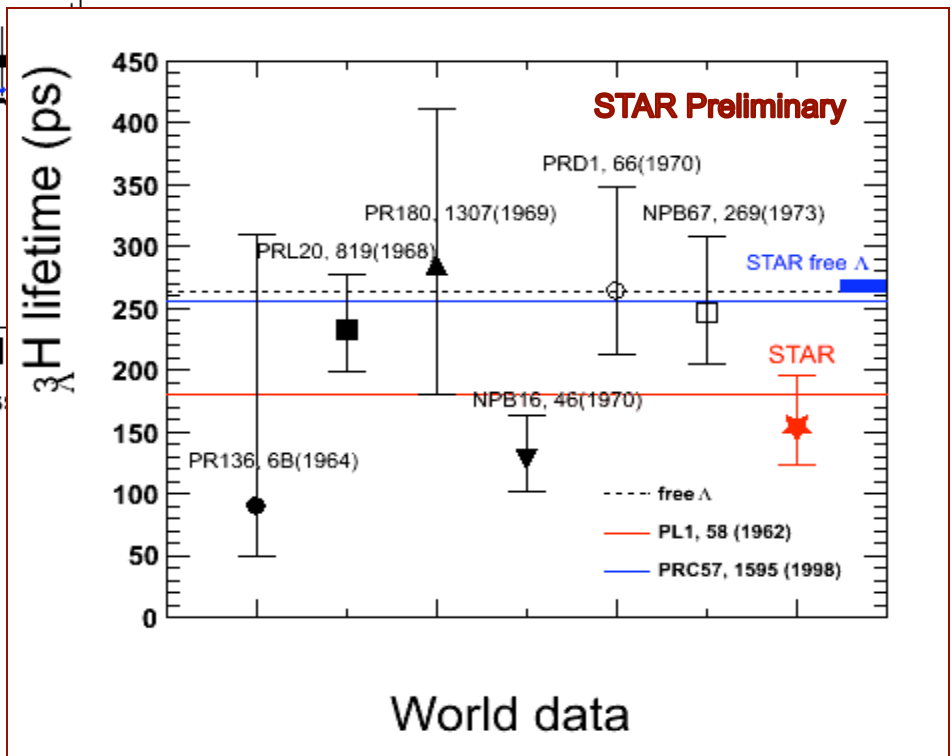
High Moment Analysis (BES)

Net-protons, Au+Au 200 GeV
$|y| < 0.5$, $0.4 < p_T < 0.8$ GeV/c

STAR Preliminary, QM09

$\langle N \rangle = C * \langle N \rangle_{7080\%} N_{part}$

Mean

$\sigma = [\sqrt{C} \, \sigma_{7080}] \sqrt{N_{part}}$

Standard deviation

$\gamma = \gamma_{7080\%} \, / \, \sqrt{C \, N_{part}}$

STAR Preliminary

Skewness

$\kappa = \kappa_{7080\%} \, / \, C \, N_{part}$

Kurtosis

N_{part}

$p - \bar{p}$: STAR Preliminary

- ○ Au+Au 200 GeV
- □ Au+Au 62.4 GeV
- ◇ Cu+Cu 200 GeV
- △ Cu+Cu 62.4 GeV

Kurtosis × Variance

N_{part}
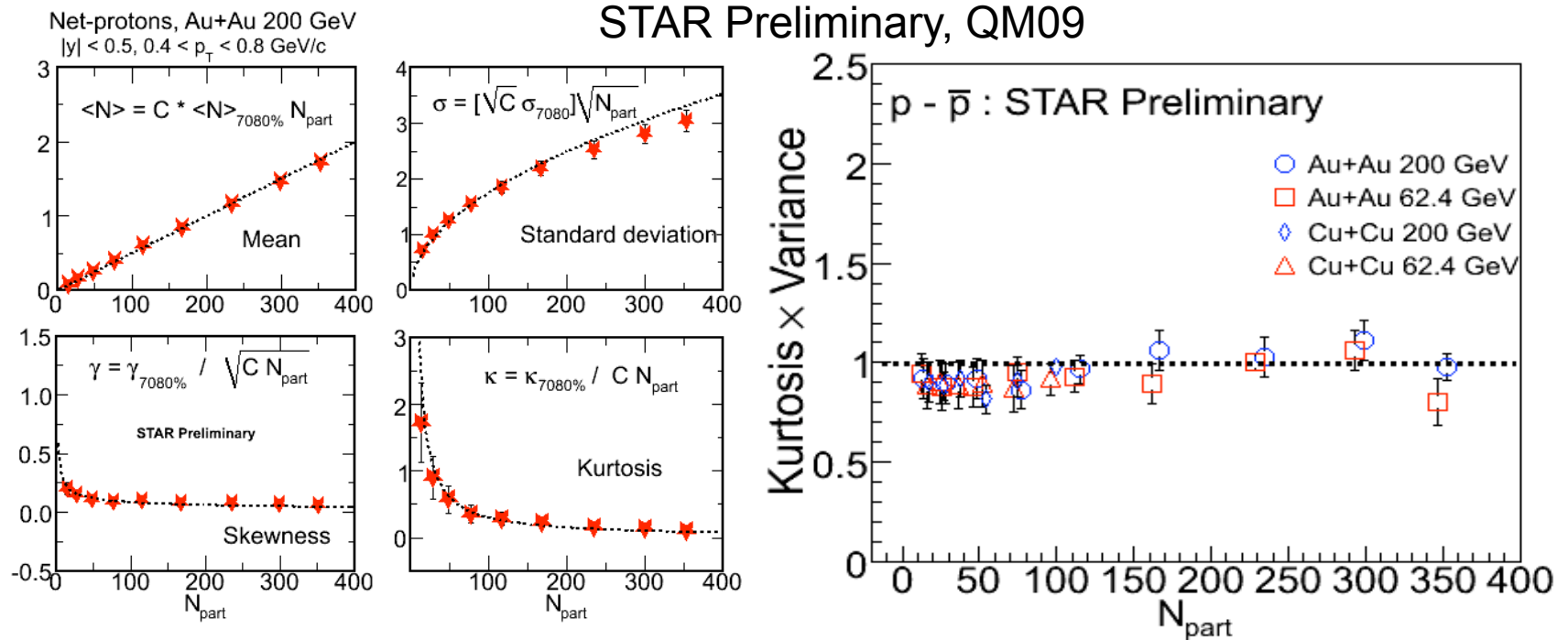
1) High moments are more sensitive to critical point related fluctuation.

2) The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility for conserved quantum numbers such as Baryon number, charge, strangeness…

# STAR Detector

MRPC ToF barrel
100% ready for run 10

MTD

EMC barrel

EMC End Cap

BBC

FMS

FPD

TPC

PMD

FHC

DAQ1000

Completed

HLT

HFT

FGT

Ongoing

R&D
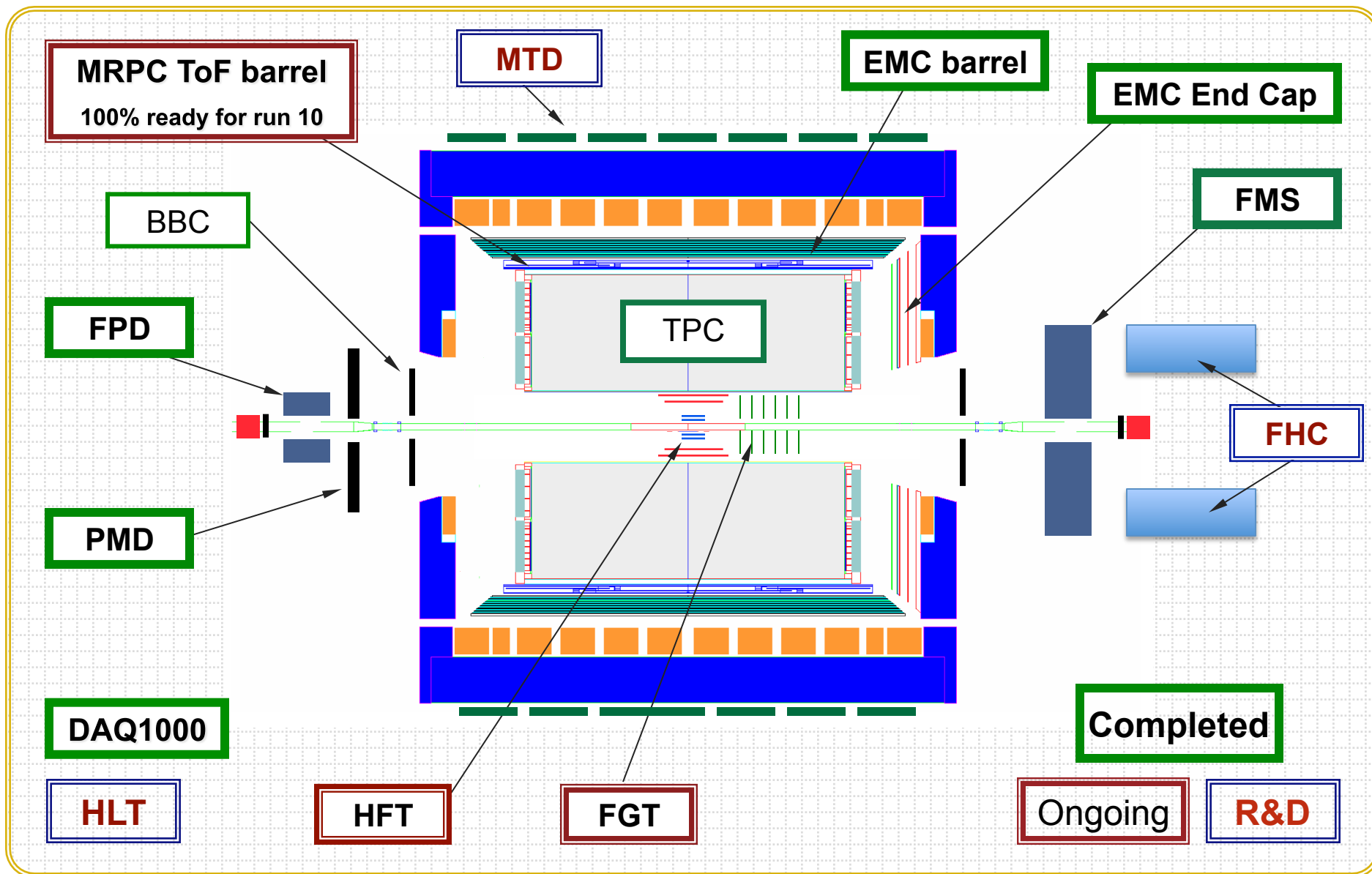
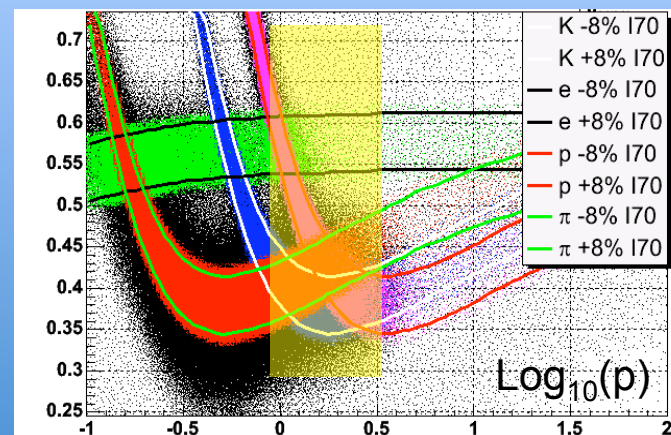# STAR: Physics with ToF

1) Significant improve PID. With TPC, PID will be been extended to p_T ~ 15 GeV/c
2) Correlations with PID hadrons; resonances (up to Ω); trigger with high p_T hadrons …
3) Beam energy scan program: event-by-event K/π analysis and net-p Kurtosis
4) 2π electron and di-electron analysis; heavy flavor program …

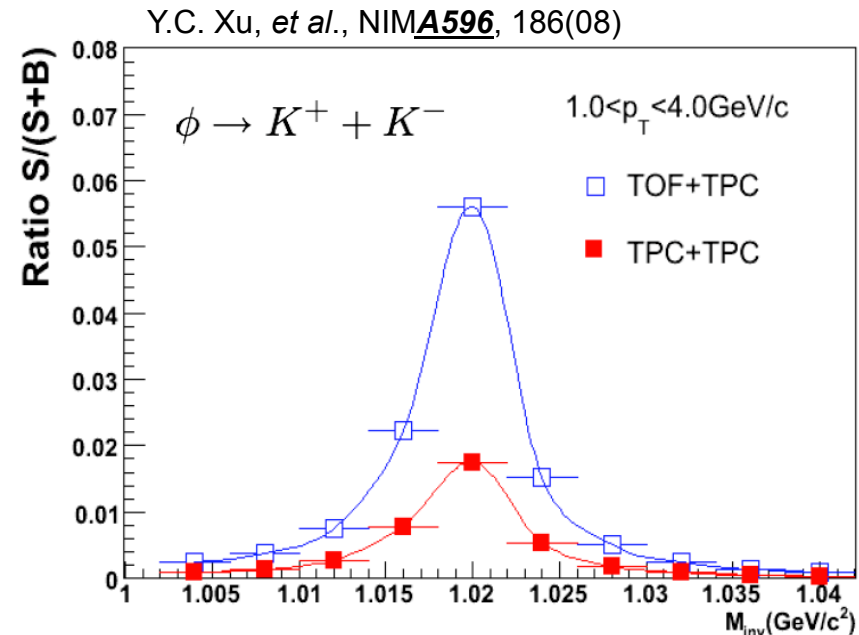STAR TOF
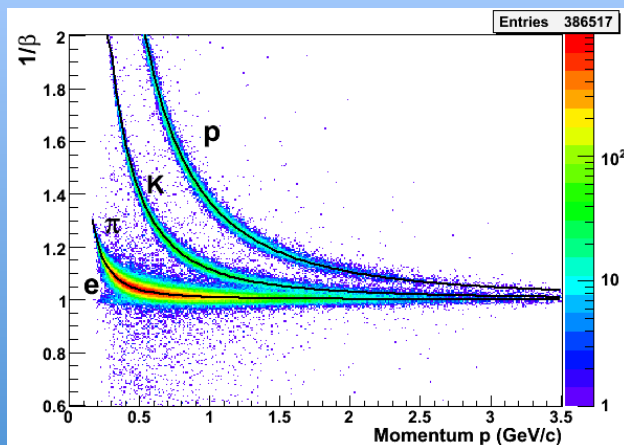
STAR TPC+TOF

Reconstruction Efficiency Improvement

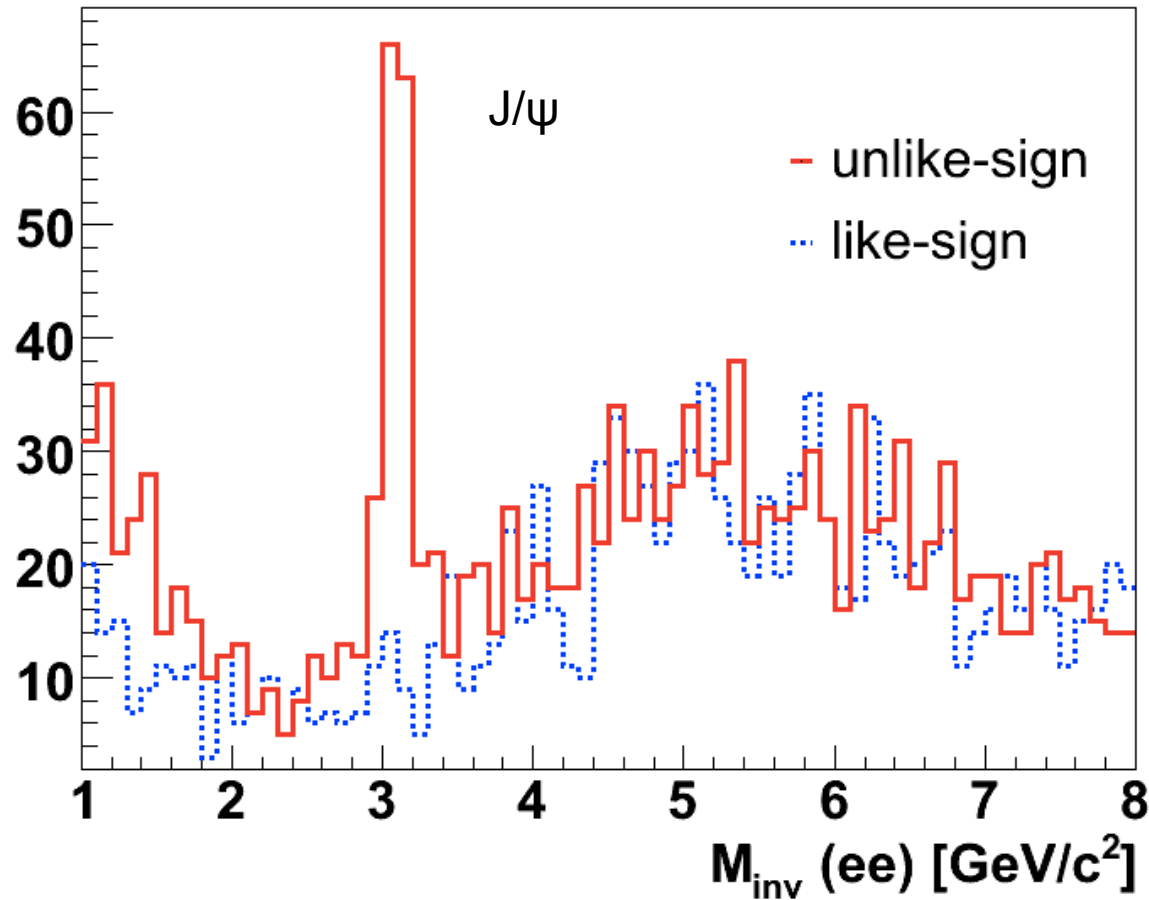Y.C. Xu, *et al.*, NIM*A596*, 186(08)
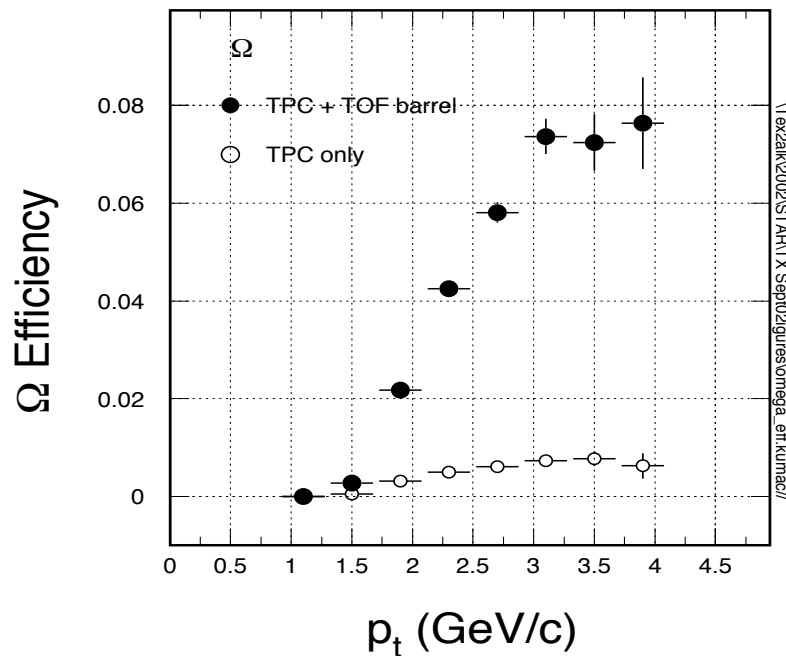
TOF:
1) Increase efficiency for all resonances
2) Extend the p_T reach

= EOS parameters: *temperature and collective velocities*
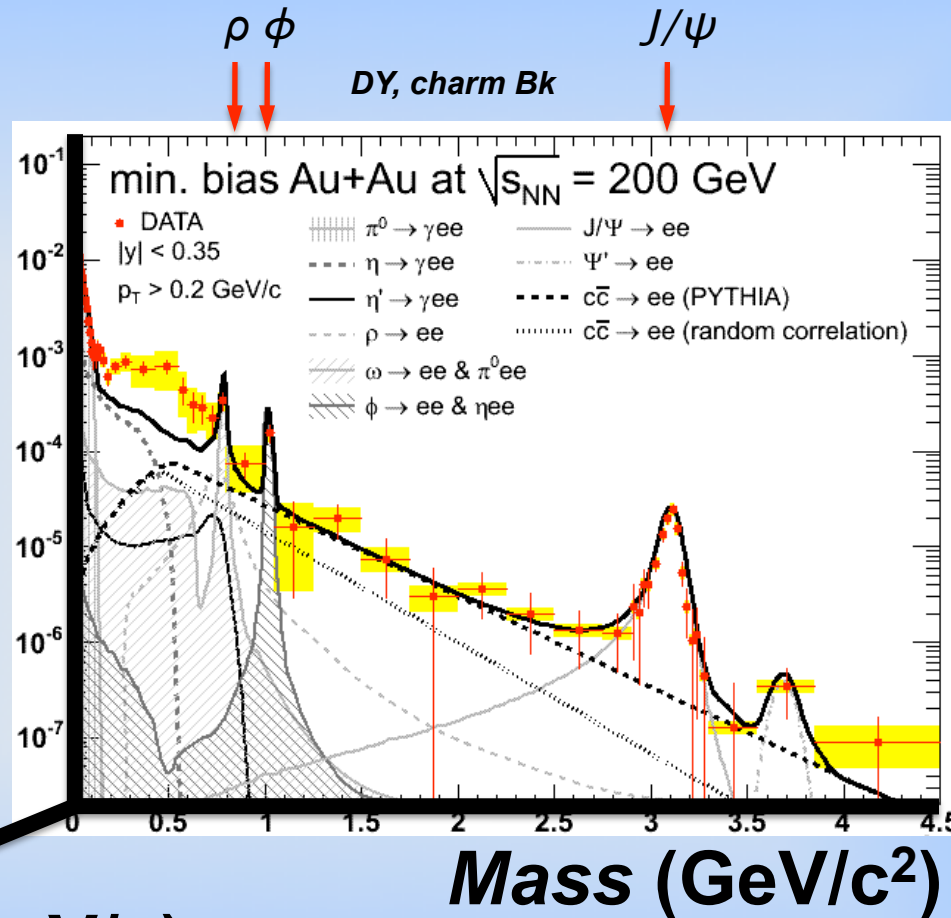
STAR High Level Trigger

Run9 p+p 200 GeV, May 19 - 25

1) Fast filtering for quick data analysis. Run10: try J/ψ v_2
2) Online QA

The di-Lepton Program at STAR

(1) σ

(2) v_2

(3) R_{AA}

ρ ϕ *DY, charm Bk* J/ψ

min. bias Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

- DATA
- $|y| < 0.35$
- $p_T > 0.2$ GeV/c

$\pi^0 \to \gamma ee$ $J/\Psi \to ee$
$\eta \to \gamma ee$ $\Psi' \to ee$
$\eta' \to \gamma ee$ $c\bar{c} \to ee$ (PYTHIA)
$\rho \to ee$ $c\bar{c} \to ee$ (random correlation)
$\omega \to ee$ & $\pi^0 ee$
$\phi \to ee$ & ηee

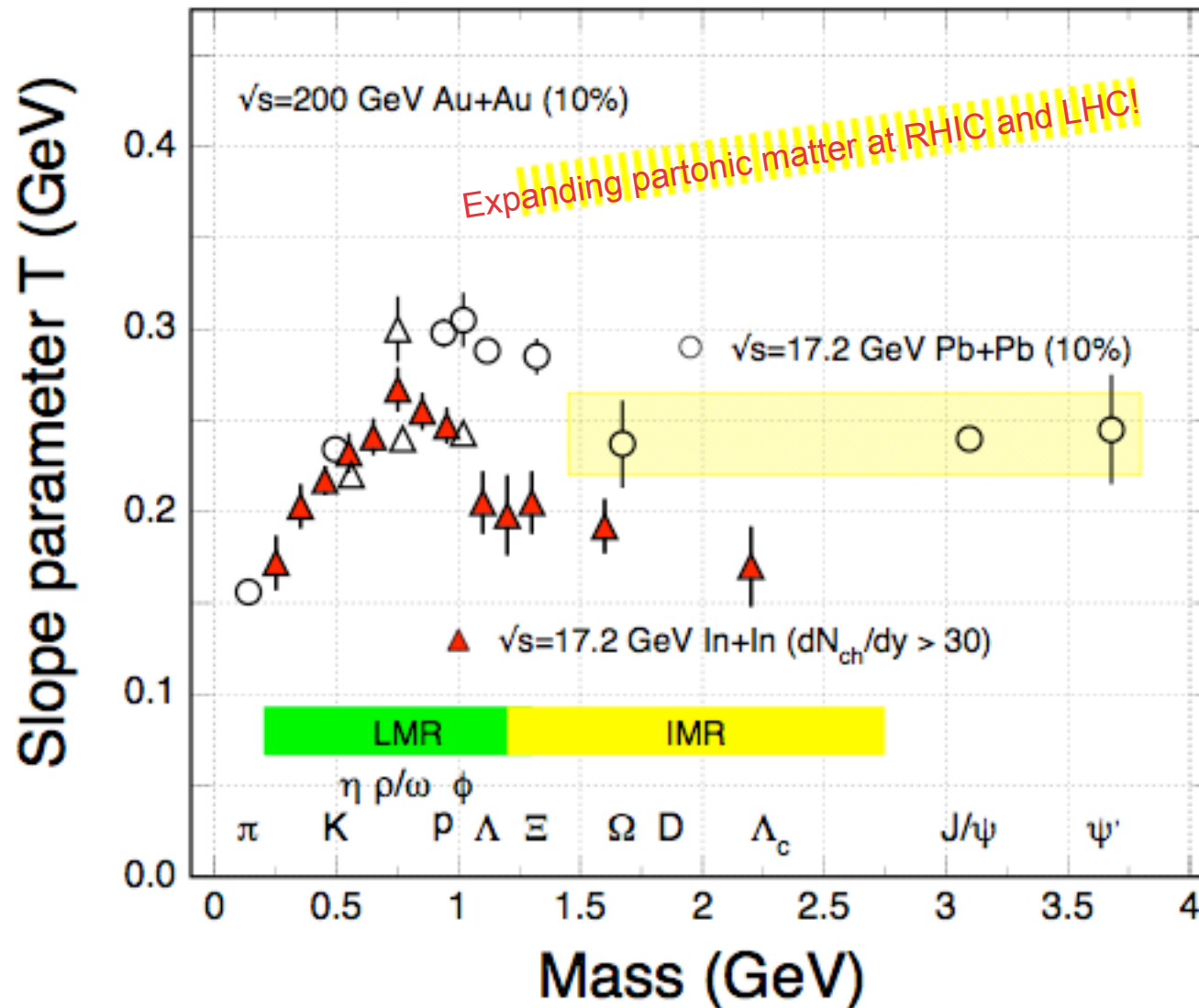**Mass (GeV/c²)**

p_T **(GeV/c)**

✓ **Chiral Symmetry Restoration**

✓ **Direct Radiation from The Hot/Dense Medium**

* **ToF Crucial for the physics.**

Direct Radiation

Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

- Low mass region:
  $\rho, \omega, \phi \Rightarrow e^- e^+$
  $m_{inv} \Rightarrow e^- e^+$
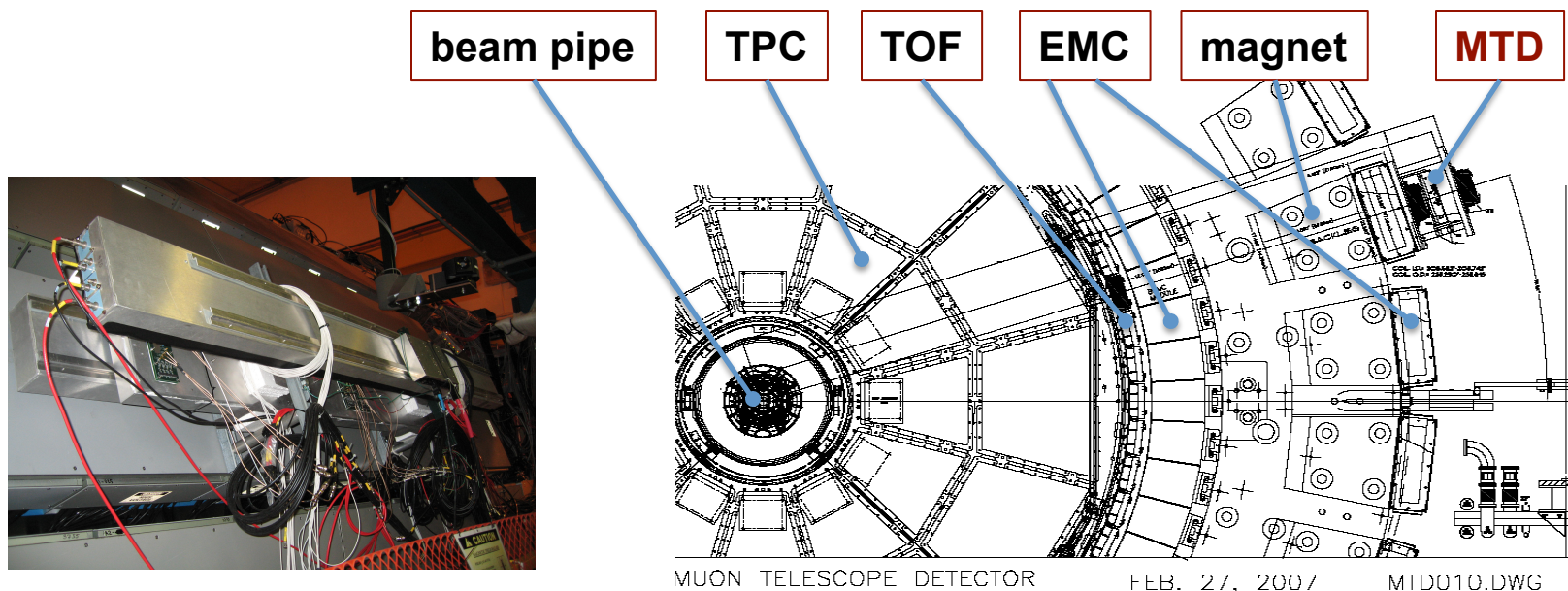
  medium effect
  Chiral symmetry

- High mass region:
  $J/\psi \Rightarrow e^- e^+$
  $m_{inv} \Rightarrow e^- e^+$

  Direct radiation

STAR: Muon Telescope Detector

beam pipe TPC TOF EMC magnet **MTD**

MUON TELESCOPE DETECTOR   FEB. 27, 2007   MTD010.DWG

Muon Telescope Detector at STAR:

1) MRPC technology; $\mu_\varepsilon \sim 45\%$; cover ~60% azimuthally and $|y| < 0.25$

2) TPC+TOF+MTD: muon/hadron enhancement factor $\sim 10^{2\text{-}3}$

3) For trigger and heavy quarkonium measurements

4) China-STAR collaboration: a proposal will be ready in mid-Sept.
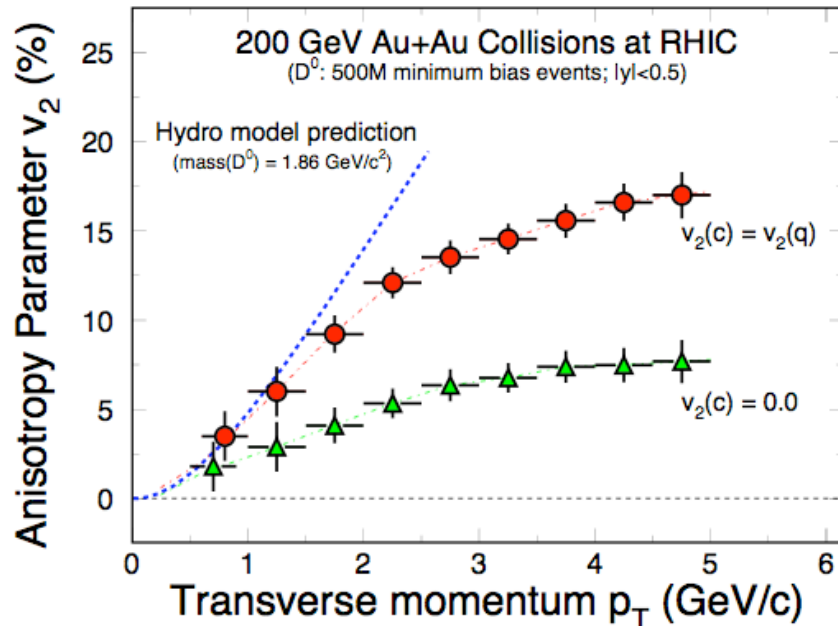
STAR Heavy Flavor Tracker
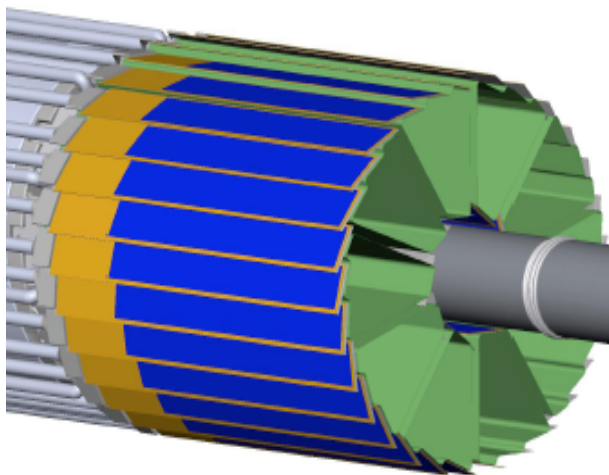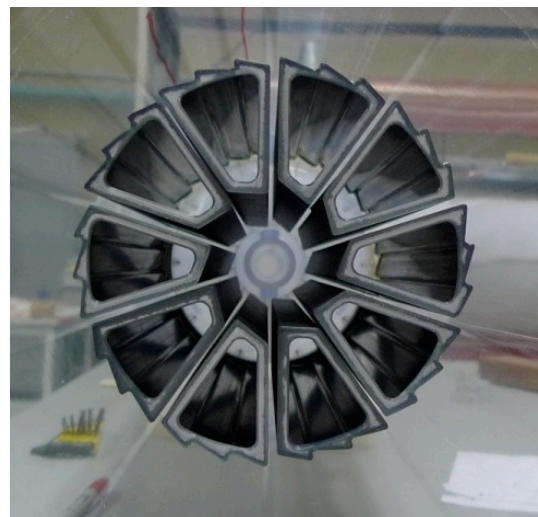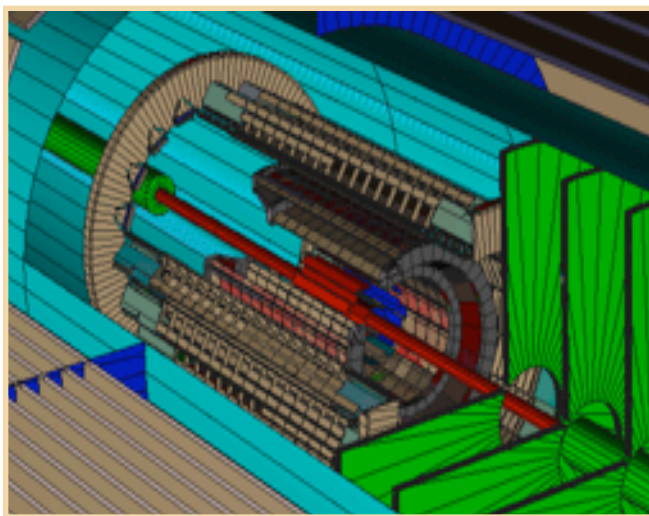
HFT: 2012-2014

1) 2-layer thin CMOS pixels;
   1-layer strips; SSD
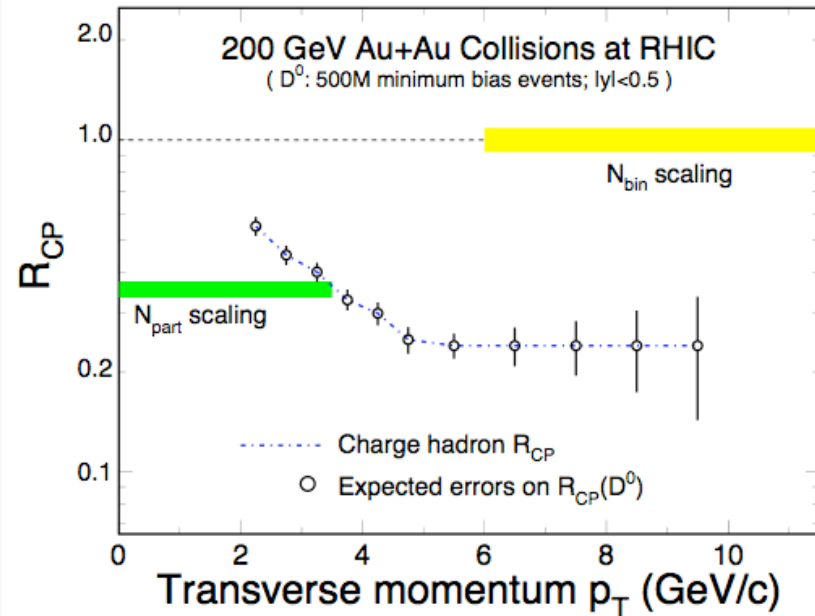2) First layer at 2.5 cm close to
   the beam pipe, 2pi coverage

➔ **Measure down to low p_T ~ 0.5 GeV/c for open charm hadrons**

HFT: Charm Hadron v_2 and R_{AA}

- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

Medium properties!

- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

Summary

STAR QCD physics program for next decade:

Spin Physics:
- 200 GeV: **Δg** inclusive and di-jets, γ-jet
- 500 GeV: **sea quark** helicity distributions
- 200/500 GeV: transverse spin phenomena

Heavy Ion Physics:
- Thermalization at 200 GeV
- QCD phase boundary and critical point
- In medium properties

Low-x Physics:
- Study gluon-rich phenomena at RHIC
- Color glass condensate

Timeline of QCD and Heavy Ion Facilities